Experimentally Validated Neutral Cluster Dynamics Model for Droplet-Based LPP Sources

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Presentation Outline

- ALPS Overview
- Work Objectives
- Neutral Cluster Dynamics
- Experimental Setup and Acquisition
- Experimental Results
- Droplet-Plasma Momentum Exchange Model
- Model Validation
- Conclusions

EUV Source Technology at ETH Zurich

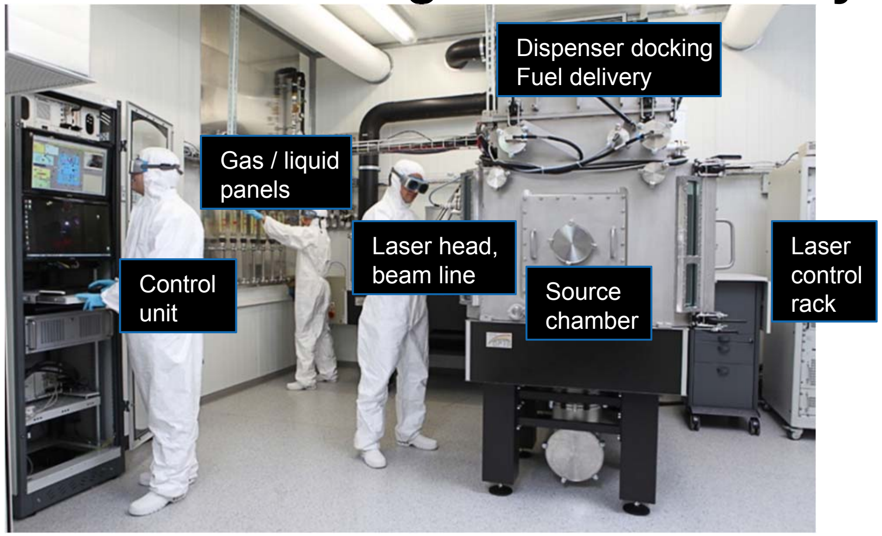
- Research & Development of **droplet-based LPP sources** since 2007
- Fully automated functioning system tested for 100‘s of hours of operation
- Main application in EUV photomask inspection, such as AIMS^{TM}, actinic blank and pattern inspection

Recent System level advancements:

- Emission stability using droplet control in time and space	(-2013)
- Characterization of source emission and debris generation	(-2014)
- Debris mitigated EUV collector	(2014)
- Cleanliness validation of tin-based LPP source after IF	(2014)

- **Life-Time assessments for 24/7 operation in industrial environment, in accordance with industry requirements in terms of tool availability and cost-of-ownership**
- **Long-term effort towards other wavelengths (Watt range)**

ALPS II EUV Light Source – Key Numbers



Parameters	Value
Laser power on target (W)	1100
Laser frequency (kHz)	>6
Laser focal spot size (µm)	70 (FWHM)
EUV source size (µm)	60 (FWHM)
Conversion efficiency (%)	>1%
Source power at the source (W)	>12
Source brightness ($W/mm^2 sr$)	350

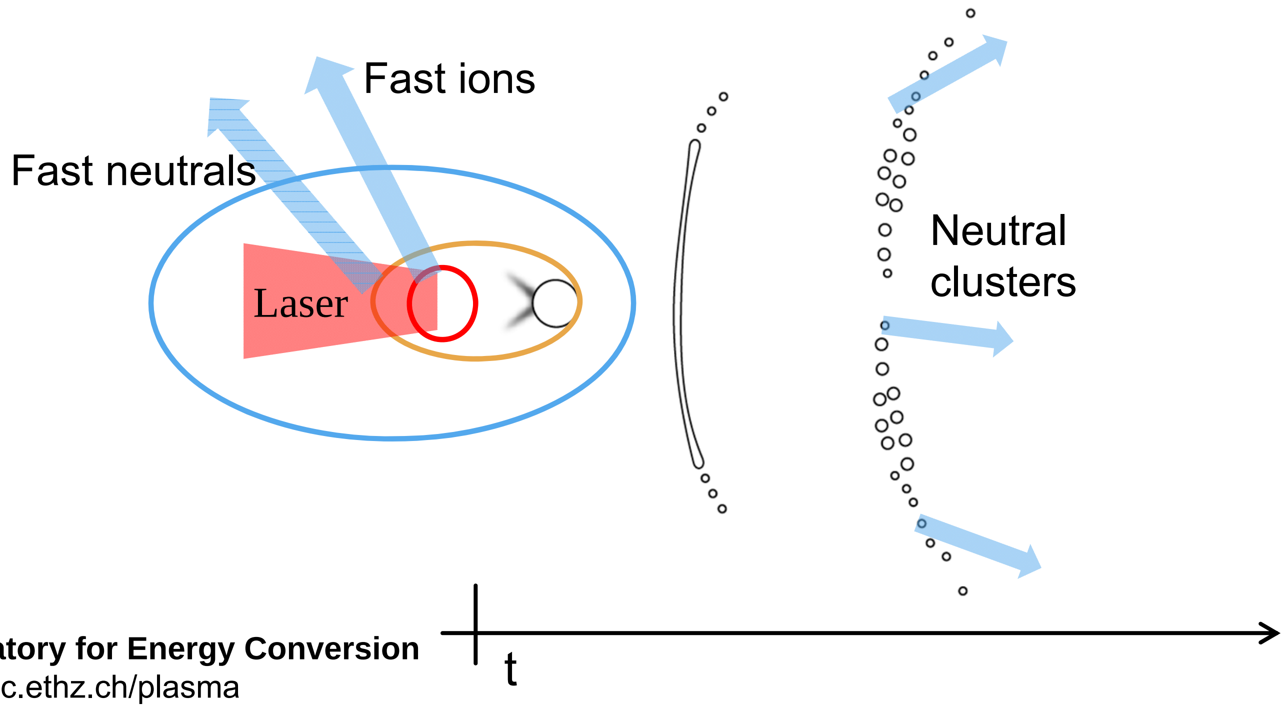
- Driven by DPSS Nd:YAG laser (average power of 1.1 kW, 1.064 µm, 6-20 kHz).
- 6th generation in-house droplet dispenser >30 µm tin droplet generation for hours of operation.
- Droplet tracking system with laser triggering on individual droplets enables droplet-laser alignment within <10% of droplet diameter.
- Full diagnostic including in-band energy monitors and out-of-band spectroscopy
- Debris mitigated grazing incidence collector, including clean IF module with imaging capability.
- Compatible with various collector configurations

Work Objectives

1. Increase source lifetime
   - Design more effective debris mitigation
   - Optimize collector region
2. Dual pulse for optimum plasma generation
   - Lower target density allows higher CE with optimized irradiance
   - Laser-induced target expansion increases coupling of target to main pulse

Laser Induced Droplet Break Up Dynamics

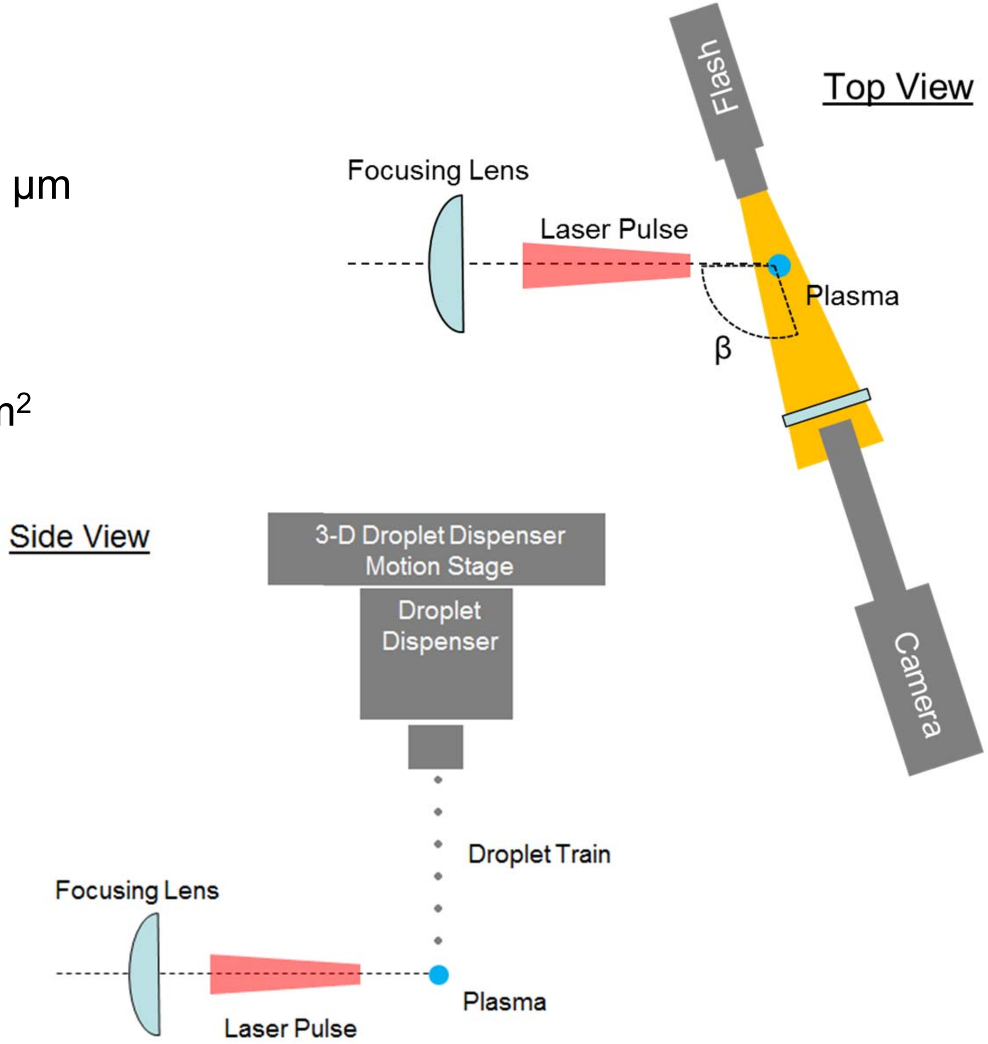
- Majority of droplet and plasma debris mass are *neutral clusters*
  - Neutral clusters are the liquid droplet fragments ejected away from the plasma region
  - This work is focused on neutral cluster dynamics*
  - Unablated droplet is flattened into a liquid disc and then breaks into small droplets
  - Plasma formation and expansion occurs within 30-40 ns, liquid deformation timescale is on the order of > 1µs
- Overall goal is to predict and to influence neutral cluster debris distribution



*submitted: D. Hudgins et al., 2015 J Phys D: Appl Phys

Data Acquisition with High-speed Shadowgraph

- Image droplet debris with a high speed shadowgraph system
- Flash duration 1 µs
- Droplet diameters varied between 50-80 µm



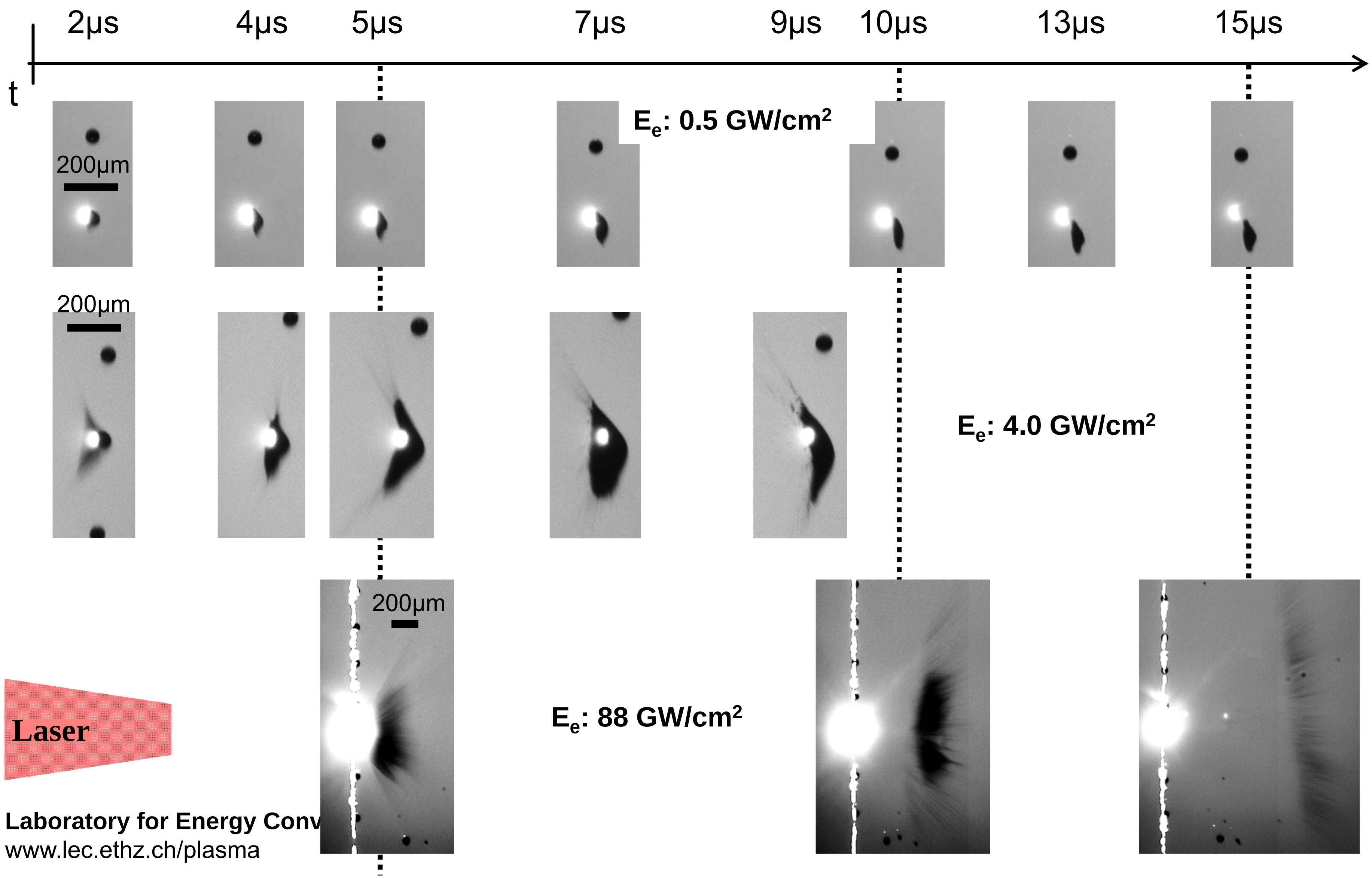
ALPS I Test Parameters

- Irradiance (E_e) varied from 5-130 GW/cm^2
- f_{rep}: 10 Hz
- $\beta = 90°$

ALPS II Test Parameters

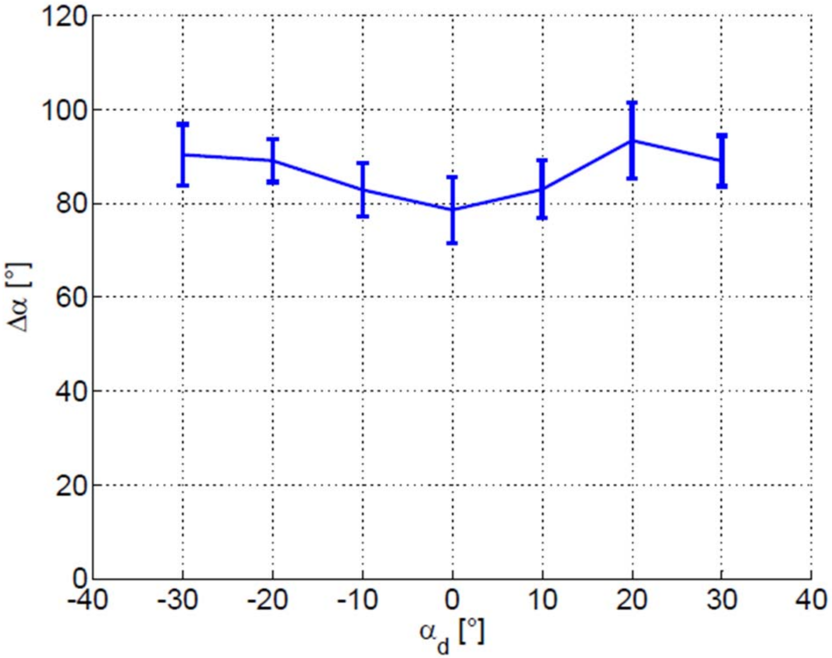
- E_e varied from 25-75 GW/cm^2
- f_{rep}: 7.3 kHz
- $\beta = 108°$

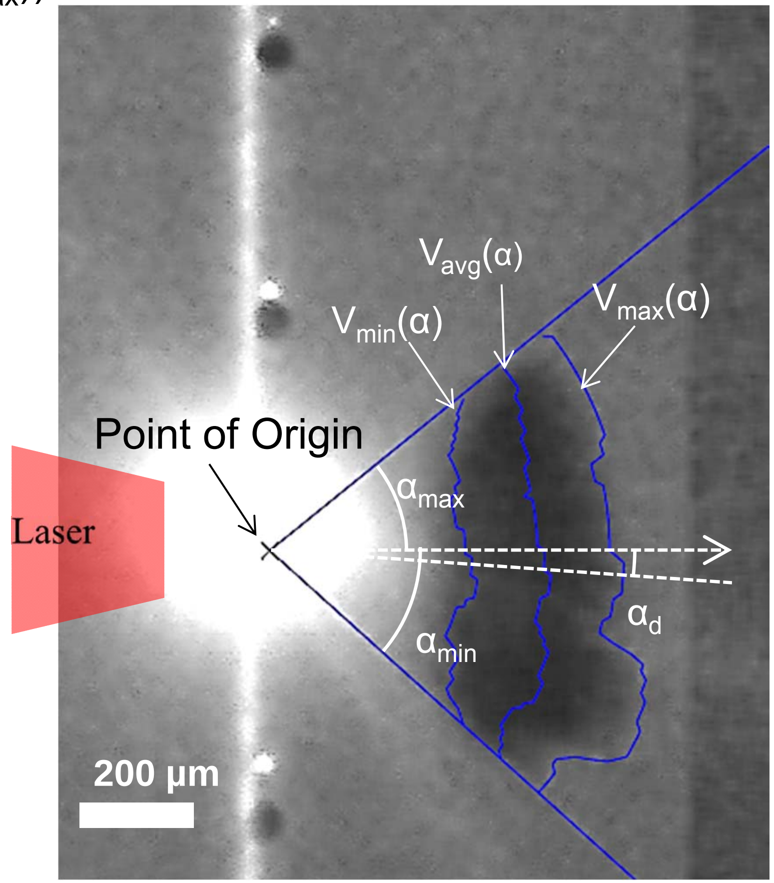
Droplet Breakup Sequences at Different Irradiances



Neutral Cluster Debris Measurement

- Image software isolates debris region measures distance from the point of origin (PoO) versus α
- Debris mean radial velocity: $\bar{V}$ = mean($V_{avg}(\alpha_{min}:\alpha_{max})$)
- Debris deflection angle: $\alpha_d = \frac{1}{2}(\alpha_{max} + \alpha_{min})$
- Debris spread angle $\Delta\alpha = \alpha_{max} - \alpha_{min}$ determines dominant neutral cluster region



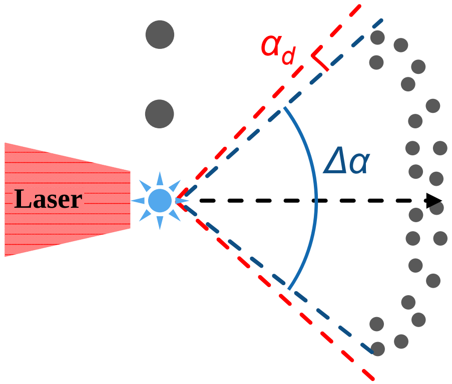


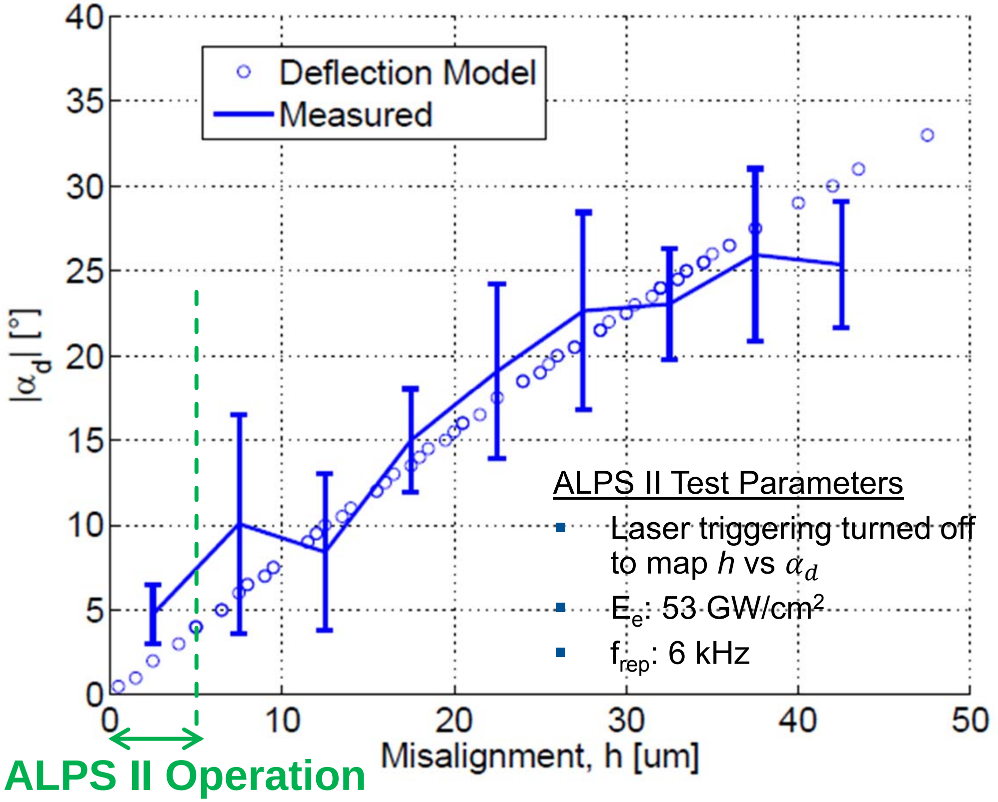
Neutral Cluster Debris Deflection

- *α_d is a function of the laser beam waist radius *w*, the droplet diameter *D*, and the droplet-laser misalignment *h*

$$\sin(\alpha_d)^3 - 2\frac{h}{D}\sin(\alpha_d)^2 - \left(\left(\frac{w}{D}\right)^2 + 1\right)\sin(\alpha_d) + 2\frac{h}{D} = 0 \qquad -\frac{\pi}{2} < \alpha_d < \frac{\pi}{2}$$

- Deflection model validated against experimental results from ALPS II
- Neutral cluster region deflection from laser-droplet misalignment (≈1°/µm)
- Collector to be positioned outside neutral cluster region α ≈ +/-50°, determined from: +/-(*Δα/2* + |α_d|)





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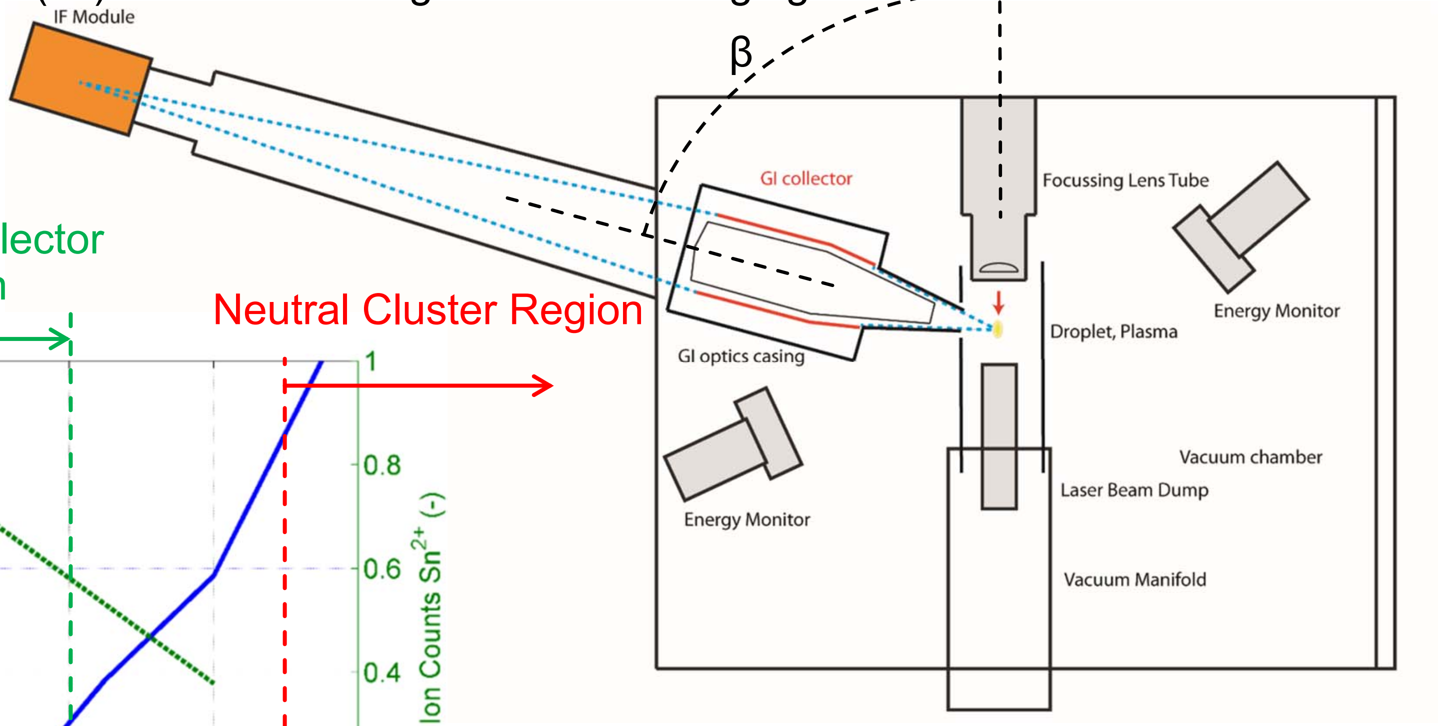
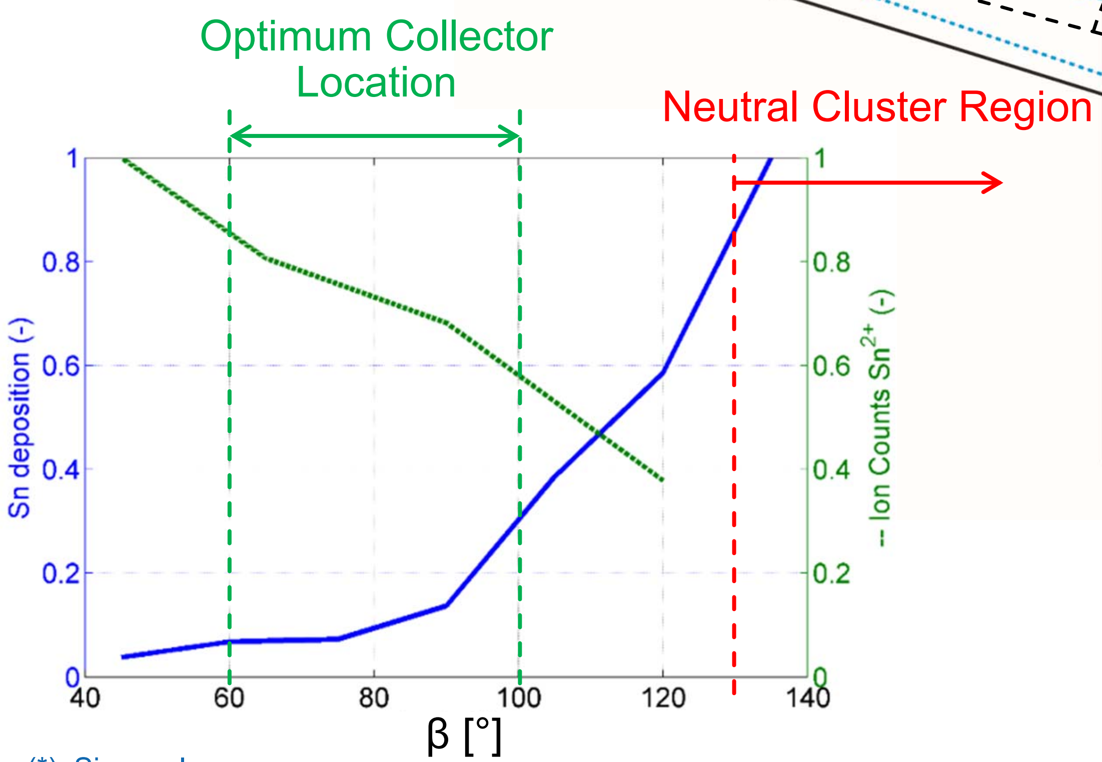
Source Collector Module

- Grazing Incidence (GI) collector for diagnostics and imaging





- Gas-based debris mitigation
- Motorized on-line alignment
- Central axis at 75° from laser axis

(*) Si sample exposure

(**) Results from electrostatic analyzer, Diss. ETH A.Z. Giovannini

Ablation Pressure-Droplet Interaction Scaling Analysis

Assumptions

- Work interaction with droplet by ablation pressure action on surface
- Ablation pressure distribution on droplet surface approx. Gaussian
- Neglect surface energy dissipation (We >> 1)
- Kinetic energy of the neutral clusters is $\approx \frac{\pi}{12}\rho D^3 \bar{V}^2$
  - Ablated layer of droplet surface δ is < 1 μm (δ<<D/6)

Ablation Pressure Work on Droplet Surface $\approx$ Kinetic Energy of Neutral Cluster Derbis

Work Transfer onto Droplet Surface from Ablation Pressure

- Peak pressure on droplet surface:

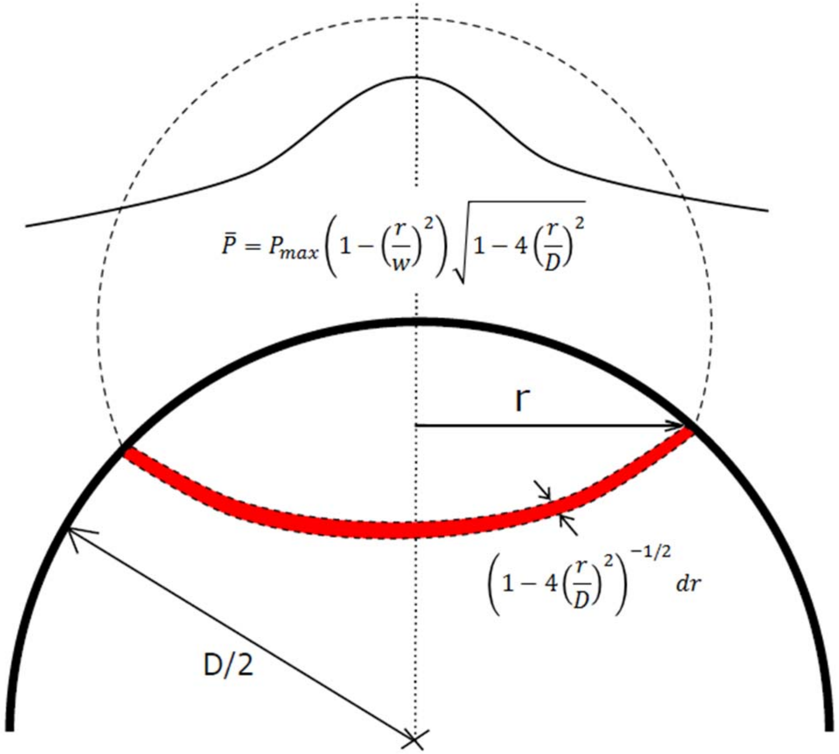
$$\bar{P} = P_{max}\left(1-\left(\frac{r}{w}\right)^2\right)\sqrt{1-4\left(\frac{r}{D}\right)^2}$$

- Pressure work*:

$$W = \frac{\tau_p}{4\rho c_0}\int \bar{P}^2 dA$$

- Ablation pressure**:

$$P_{max} \cong 8 \cdot I_0^{\,0.7} \Big/ \left(1+\frac{l_{ac}^{(0)}\sin(\theta)}{w}\tau_p^{\,0.9} I_0^{\,0.3}\right)^{1.4}$$



- c_0 = liquid sound speed
- τ_p = laser pulse duration
- ρ = density
- D = droplet diameter
- $l_{ac}^{(0)}$ = nominal critical surface distance
- w = $1/e^2$ beam waist radius
- P_{max} = peak ablation pressure
- I_0 = Laser Irradiance
- θ = ray convergence angle

*Trucano T G, *et. al.*, 1995 *Int. J. Impact Eng.* **17** 873-90
Harrach R J, *et. al.*, 1982 *AIP Conf. Proc.* **78 164-8

Non-dimensionalized function relating $\bar{V}$ to ablation pressure

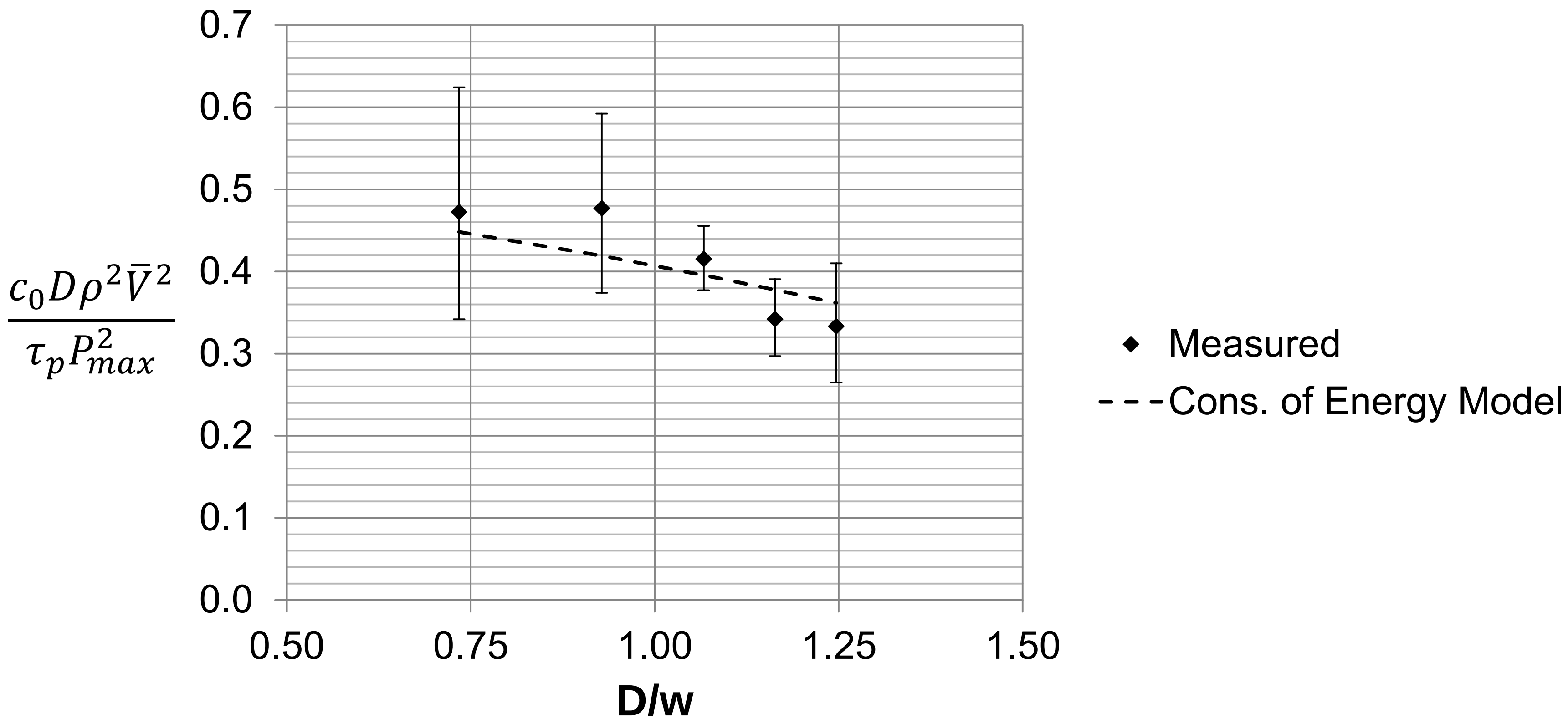
- Neutral cluster velocity for constant irradiance with Nd:YAG:
  - Change in droplet size, $\approx \bar{V} \propto D^{-0.8}$
  - Change in pulse duration $\approx \bar{V} \propto {\tau_p}^{0.3}$
  - Change in spot size $\approx \bar{V} \propto \ln(w)$
- Behaviour of other fuel droplets possible with known dependence of ablation pressure on laser parameters
- Since $\bar{V} \propto P_{max}$, $P_{max} = f\left(E_e, \tau_p, w, \lambda\right)$ can be approximated from $\bar{V}$ measurement

- $\bar{V}$ = mean radial neutral cluster velocity
- P_{max} = peak ablation pressure
- c_0 = liquid sound speed
- τ_p = laser pulse duration
- ρ = density
- D = droplet diameter
- w = $1/e^2$ beam waist radius

$$\boxed{\frac{c_0 D \rho^2 \bar{V}^2}{\tau_p P_{max}^2} \approx \frac{1}{140} \cdot \begin{cases} \left(\frac{D}{w}\right)^4 - 14\left(\frac{D}{w}\right)^2 + 70, & \frac{D}{w} \leq 2 \\ \left(1 - \left(1 - 4\left(\frac{w}{D}\right)^2\right)^{7/2}\right)\left(\frac{D}{w}\right)^4 - 14\left(\frac{D}{w}\right)^2 + 70, & \frac{D}{w} > 2 \end{cases}}$$

Model Validated with Variation of Irradiance and Droplet Diameter

- Measurements taken in ALPS II facility, f_{rep}: 7.3 kHz
- Sn droplet diameters varied 50-80 µm
- Irradiance varied from 25-75 GW/cm^2



- **Model consistent over a wide parameter space**

Conclusions

- Results show that ablation pressure interaction is the main momentum exchange mechanism between plasma and remaining liquid
- Pre-pulse laser for dual pulse operation can be sized
  - For a specified target expansion speed and wavelength the model determines pulse energy, spot size, pulse duration
  - Deflection model determines the pre-pulse laser spot size for required target orientation stability
  - Expanded target improves laser-target coupling for sources with larger spot sizes
  - Shaped target atomizes into smaller fragments after main pulse
- Source optimization:
  - Factors influencing neutral clusters are known
  - Optimize collector position
- Model used as a basis for modelling the droplet deformation and debris distribution
  - Fluid dynamic model of fast pressure impulse interaction with droplet

Acknowledgments

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